# New Problems for a New Century

R. D. Blandford

February 1, 2008

## 1 Introduction

This is an optimistic time in X-ray astronomy. Chandra and XMM-Newton are fully operational and producing results at an undigestible rate; Astro-E has been rescheduled for a 2005 launch and will then assume its place as the third essential component of contemporary missions. HETE-II is reportedly performing flawlessly and Swift is on track for a 2003 launch. Two major international missions, Constellation-X and XEUS, as well as a host of smaller projects are at various stages of development.

My task is to provide some overview of what we have learned here and, especially, to suggest some questions that should be addressed in planning new missions. I will have to be somewhat selective and idiosyncratic in what I discuss and will refer to the accompanying articles, using brackets, for more extensive discussions. As the meeting has been organised along astronomical lines, I will attempt an orthogonal organization and try to bring out some connections by concentrating on the underlying physics.

However, before doing this, I would like to recall the scientific context in which Chandra, XMM-Newton and Astro-E were first proposed. The big issues in 1977, when Chandra was proposed were the X-ray background and quasars, the two being thought to be closely related. In addition, there was an understandable envy of optical astronomers and a strong belief that arcsecond imaging would transform our view of the high energy universe. For XMM-Newton, in 1982, the prospect of high dispersion spectroscopy and the ability to perform abundance analyses and velocity measurements were strong motivators. By the time that Astro-E was conceived, around 1991, the lure of the hard X-ray band and, in particular, iron lines was irresistible and it was appreciated that, despite their lower luminosity, the stronger fluxes from Seyfert galaxies and their more rapid variability recommended them as suitable sources with which to study the general properties of AGN. In fact, as we have seen here, these have turned out to be pretty good scientific justifications for the two missions that have been launched and the one whose successor we eagerly await.

X-ray astronomy has become a far richer field than anticipated by these proposals. While some problems, like the X-ray background, supernova remnants, clusters and accretion disks around cokpact objects appear to have been broken, albeit leaving a lot of crucial details to be filled in, others, like GRBs have become extremely interesting and have developed in quite unexpected directions. Completely new phenomena like the Galactic Ridge X-ray Emission and X-ray protostars of all types, which were widely discussed here, have been

uncovered. On the technological front there have been tremendous advances culminating in the microcalorimeter arrays which are anticipated to lie at the heart of future advances in X-ray spectroscopy.

If I turn now to the future and look at the Constellation-X [White] brochure I see black hole astrophysics, "astro-ecology", and mapping the distribution of dark matter as the principle scientific challenges. For XEUS [Jansen], the emphasis is a little more cosmological and we must add the first groups and quasars, the history of metal production and the astrophysics of the hot intergalactic medium. It will be fascinating to see how these drivers evolve over the coming decade.

# 2 Ten Questions for a New Decade

In order to enter into the spirit of this meeting, I would like to present ten fundamental astrophysical or even physical questions that I believe can be addressed by X-ray astronomy.

## 2.1 How do Cosmic Magnetic Fields really Behave?

Cosmic magnetic field, on all scales is generally described under the MHD approximation. Physically, MHD rests on two complementary principles, that magnetic field is frozen into moving fluid – "go with the flow" – and that the anisotropic, magnetic stress tensor is be responsible for directing the flow – "push-pull". However, even if these principles suffice, almost always and everywere, they do not tell the whole story. Shocks, reconnection sites and finite Larmor radius effects can all lead to behavior that is not consistent with the precepts with the precepts of MHD. It is only though observations, interpreted using numerical simulation, that we are going to understand how magnetized fluid really behaves under cosmic conditions.

X-ray observations reported here are providing vital clues in a variety of environments. All four types of protostar are found to be X-ray sources along with brown dwarfs [Kuboi, Linskey], suggesting that coronae are commonly energised, presumably magnetically, to form high temperature gas. Disk accretion, likewise, shows signs of magnetic activity [Mukai, Kubota, Mineshiga]. At the other end of the scale, many putative black holes in galactic nuclei are found to be spectacularly underluminous, with powers as low as $\sim 10^{-8}L_{\rm Edd}$ or $\sim 10^{-5}L_{\rm Bondi}$ [Mushotzky]. This is a very powerful clue as to how magnetic viscosity develops in accreting systems. A quite different consideration is important in rich clusters of galaxies where the Coulomb scattering mean free path is so large that magnetic field must be invoked to limit the heat transport.

## 2.2 How do Cosmic Plasmas really Behave?

Magnetohydrodynamics is only an approximation to the full, kinetic behavior of plasma, dealing, as it does, with the large scale conservation of mass, momentum and energy. Plasma effects may be vital to understanding the Galactic Ridge emission [Tanaka] observed from the Galactic bulge. Collective interactions, like transit time damping, rather than pure two body Coulomb interactions may play a role in electron-ion equipartition. These considerations are

of vital importance to understanding stellar coronae [Linsky] as well as accretion disk coronae and adiabatic accretion in the underluminous sources found in galactic nuclei. They are of no less importance to understanding the thermal balance of hot gas in clusters and the general intergalactic medium and may provide the explanation for why lines from intermediate states of ioniziation, such as would be expected from cooling gas in ionization equilibrium, are generally not seen in cluster spectra.

In addition, I suspect that plasma physics will ultimately be needed to resolve the controversy concerning the X-ray spectra of Seyfert and LINER accretion disks [Kahn, Iwasawa, Brandt, Boller, Nandra, Zdziarski, Reeves, Yaqoob]. However, before this happens some purely observational differences must be resolved. How wide and variable are the Fe lines? How much of the observed spectrum is imprinted by the warm absorber? Are broad lines of lower Z elements really present in the spectrum?

## 2.3 What is the Structure of Collisionless Shocks?

Plasma physics is also crucial to the structure of collisionless shocks which are essential to X-ray astronomy as this is almost the only way to heat gas to high temperature in the interplanetary, interstellar and intergalactic media. (Bulk, dissipative heating may be occuring in accretion disks, but even here, this poses problems.) Shocks also accelerate relativistic electrons. They inevitably arise when bulk speeds become supersonic either in expanding flows like stellar winds (Linsky) or as a consequence of gravitational acceleration during structure formation in the expanding universe.

Observationally, we are having a hard time locating shocks. There are very few supernova remnants where we can be sure that we have identified the outer blast wave [Peter, Aschenbach, Kamae]. Similarly, with the accretion shocks around clusters [Bautz, Arnaud] and even the Galactic center [Koyama]. These shocks are responsible for heating gas, accelerating cosmic rays and, possibly, stretching magnetic field lines by large factors. However, we do not understand electron-ion equipartition, whether cosmic rays actually mediate the shock compression and how and whether fields are amplified. This last point is particularly relevant to the mildly relativistic shocks observed in X-ray afterglows from $\gamma$-ray bursts, where almost all contemporary models invoke an immediate and magical post shock field enhancement to a fraction of the equipartion value that is just one of many free parameters in the fitted spectra [Ricker, Nousek, Fiore]. We really need a more basic understanding of what is happening and the best approach involves careful analysis and simulation of the glorious observations of supernova remnants shown here.

## 2.4 When and how were the Elements Made?

These same observations provide *prima facie* evidence that heavy elements are synthesized during supernova explosions [Iyudin, Petre, Aschenbach]. However, the details remain elusive. We really have no working model of type II supernovae, cannot tell, for example, whether a neutron star or a black hole has been left behind in Cas A and we are in the embarassing position that we cannot even agree upon the progenitors of type Ia supernovae, that are so vital to contemporary cosmography. X-ray observations really provide an excel-

lent handle on the models, probing as they do the mass cut in the explosion of heavy stars, the extent of the inhomogeneity induced by the explosion, the strength and angular distribution of the wind and the centering which also relates to the recoil speed of the remnant star.

There are other, conjectured sites of nucleosynthesis, especially of r-process elements, like hypernovae and neutron star coalescence [Nomoto] and where X-ray observations can be vital, such as the Fe lines reported from GRBs [Fiore]. On the large scale, opnservations of distant galaxies can explore abundance gradients and provide a quantitative measure of the history of star formation [Fabbiano, Iwasawa]. Indeed, claims of abundance enhancements as large as [Fe/H] $\sim 5$ have been made for the centers of galaxies and in rich clusters [Ohashi, Bohringer].

## 2.5 How does Matter Behave at High Density?

One of the more important ways through which X-ray astronomy can repay its debt to fundamental physics is to determine the equation of state of cold nuclear matter at supranuclear density [Tsuruta, Weisskopf]. We really have little idea from basic physics as to whether the interiors of neutron stars contain free quarks, pion or kaon condensates or just a proton superconductor plus neutron superfluid as conservatively! assumed. X-ray observations are the way to find the answers. This investigation complements the studies of hot nuclear matter being performed at heavy ion colliders and is quite possibly relevant to the early universe.

The most direct method is to measure the mass-radius relation of neutron stars using estimates of the gravitational redshift and the surface gravity. In practice, this is now appearing to be a more difficult task than originally envisaged due to the absence of spectral lines. As feared, the surface composition is largely H and He and there are no strong lines.

A second approach, is less direct but currently more productive. This involves measuring the cooling rate by comparing the measured surface temperature with the ages of the surrounding remants. As neutron star atmospheres and our understanding of remnant dynamics improve, this should become a far more prescriptive as the cooling rates are strongly sensitive to the interior composition.

A third approach is to use the frequencies of neutron star QPOs, though this will require a much more sophisticated understanding of their dynamics than we have at the moment.

## 2.6 Is General Relativity Correct?

In addition to probing nuclear physics, X-ray astronomers have the opportunity to provide quantitative probes of strong gravity, specifically by detecting physical effect that are predicted by the relativistic description of the spacetime around a spinning black hole [Yaqoob]. The Kerr metric is the default description and it will take hard evidence to persuade most relativists that it is wrong or incomplete. However, it logically possible that black holes are more hirsute than conventionally thought and that particle (including photon) motion is affected.

To date most attention has centered around attempts to measure the second parameter, the spin or, equivalently, the specific angular momentum. The width of the Fe line has been

taken as demonstrating that the orbiting gas gets close to the horizon and that, consequently, holes spin fast. There are some ongoing concerns about the strength and widths of these lines. In addition, some "Devil's Advocates" have claimed that they can be formed by gas plunging into the horizon. However, it will be hard to make it convincingly quantitative until we understand the radiative transfer. I suspect that there is more promise in the "diskoseismology", so comprehensively studied most recently using RXTE [Swank]. Here, there have also been claims for the detection of spin on the basis of some quite simple and to me, not yet compelling descriptions of what is going on. However, remarkable patterns are starting to emerge among the frequencies and spin must be a major factor in setting the clock. (The observed QPOs are far too hard for the emission to arise from the disk.) It would be wonderful if we could recapitulate the early history of atomic spectroscopy and create a redundant, theoretical description of these modes that verified the detailed form of the Kerr metric.

## 2.7 What is the Nature of Dark Matter?

An even larger physics challenge is to identify the dark matter and chronicle its role in the development of large scale structure. Despite the, perfectly reasonable, focus on neutral supersymmetric particles, and to a lesser extent, axions, we really don't understand what it is. X-ray astronomy can contribute in a major way by helping trace the shape of the potential well around ellipticals, groups and clusters [Bautz, Boehringer, Ohahshi, Arnaud]. In the last case, velocity dispersions, Sunyaev-Zel'dovich dips and weak lensing can all be combined to produce a comprehensive picture. So far, the most important impression left by the X-ray observations is that many, though not all, clusters are surprisingly inhomogenous despite the apparent regularity embodied in the $L-T$ relation.

## 2.8 How did the Universe Expand?

On the larger scale, CMB and SNIa observations have produced an impressive body of evidence that our 14 Gyr old universe is flat, mostly dark and accelerating. Presuming that this result holds up, it is partly quite unexpected and even more perplexing. (It should not be forgotten that, for a long while, the most compelling evidence that the Einstein-De Sitter universe was not even a close approximation to the truth, came from X-ray observations of clusters [Henry, Mitsuda].)

The long term kinematic goal must surely be to measure the variation of the scale factor $a(t)$ with cosmic time in a manner that is independent of dynamical assumption. (We do not know if the so-called dark energy is a manifestation of a shortcoming in the left hand side or the right hand side of Einstein's Field Equations, or both.) It is the eternal hope of observational cosmology that standard rods and candles will be found extending out to large redshifts and X-ray sources, particularly clusters, may yet turn out to be examples [Hasinger].

## 2.9 What were the First Structures in the Universe?

Although, it is commonly believed that normal galaxies assembled from the merger of smaller subunits and that they, in turn congregated into clusters, we still do not what were the first self-gravitating structures to form in the expanding universe. What we do know is that powerful quasars were already functioning when the universe was less than $\sim 800$ million years old. This implies that black holes assembled very early in the life of galaxies and probably played an important role in galaxy formation. Although many of these black holes are likely to be obscured, their hard X-ray emission can be seen redshifted into the intermediate X-ray energy band.

Alternatively, perhaps the first self-gravitating objects were "Population III" stars, that formed inside small dark matter halos, and which subsequently turned into some of the "Intermediate Black Holes" the powerful X-ray sources with luminosities in excess of the Eddington limit for $\sim 100$ $M_{\odot}$ stars, seen in nearby galaxies or the X-ray binaries found in globular clusters [Mushotzky].

## 2.10 How do you do X-ray Astronomy from the Ground?

Much of this meeting has been concerned with recent ideas and progress in mirror and detector development throughout the entire X-ray band [Elvis]. The prospect of pushing focusing optics beyond 100 keV [Strüder, Takahashi] and of deploying large microcalorimeter arrays is indeed an exciting one [Stahle]. Looking further ahead, the time is surely ripe to start doing polarimetry again and work towards making far more sensitive X-ray polarimeters. (I note that it has recent proved possible to measure X-ray circular polarization from laboratory synchrotrons.)

There is even considerable enthusiasm for attempting X-ray interferometry from space [Cash]. In its most elemental form this is effectively a Young's slit experiment which should appeal, at least in principle, to any physicist. How long it takes to develop a system capable of accomplishing the stated goal of imaging a black hole remains to be seen, but there are several important milestones along the way which could lead to more broadly applicable technology development.

Among several other approaches to understanding the extreme physical conditions within the sources are high energy density experiments at laser facilities, numerical simulation, especially of three (and four) dimensional magnetohydrodynamics and laboratory astrophysical studies to augment our library of wavelengths, oscillator strengths, collision integrals and so on that will be necessary for us to interpret X-ray observations of hot plasma[Porter].

It will be interesting to see if the questions that have motivated proposals for the next generation of X-ray observatories fare as well as those that motivated Chandra, XMM-Newton and Astro-E.

# Acknowledgements

I thank Professor Kuneida for the invitation to attend this meeting and his hospitality and several other participants for helpful advice.